Enabling Technologies for Ultra-Safe and Secure Modular Nuclear Energy Advanced Research Projects Agency – Energy

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Sandia National Laboratories and General Atomics are pleased to respond to the Advanced Research Projects Agency-Energy (ARPA-e)'s request for information on innovative developments that may overcome various current reactor-technology limitations. The RFI is particularly interested in innovations that enable ultra-safe and secure modular nuclear energy systems. Our response addresses the specific features for reactor designs called out in the RFI, including a brief assessment of the current state of the technologies that would enable each feature and the methods by which they could be best incorporated into a reactor design. These features are:

- *Mostly autonomous operation*: Technologically, this is currently possible. However, operations must be considered in context with the need for safety, security, and safeguards requirements. Concurrent Engineering (CE) practices are used in other industries and studies have been performed to show how this can be utilized for small modular reactors (SMRs).[1,2] Through DoD efforts, more robust controls systems have been developed that make more secure, mostly autonomous operations possible. These techniques can be used for reactors.

- *Walkaway-Safe*: Some current water-cooled reactors claim to have been designed to be walkaway-safe. However, safety is strongly coupled with other key reactor characteristics. It must be considered concurrently with security, safeguards, and operations. For this feature, CE practices may also be implemented to support SMRs.[1,2]

- *Refueling Cycle > 10 years*: Currently, accident-tolerant fuel must still be tested and approved for low-enrichment applications. Developing reactors with neutronics characteristics capable of long refueling cycles (up to 30 years) with low-enriched uranium has been shown to be relatively simple. However, developing fuels and claddings that can withstand the neutron fluence and high temperatures over this time period while still containing the associated fission product gases and maintaining integrity is very difficult. Currently, ceramic matrix composites are being tested in multiple research and test reactors and show promise, but further testing and validation is needed.

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[1] Middleton, Bobby D. and Carmen Mendez, "Integrating Safety, Operations, Security, and Safeguards into the Design of Small Modular Reactors," Proceedings of the ASME 2014 Small Modular Reactors Symposium, SMR2014-3336, April, 2014.
[2] Middleton, Bobby and Carmen Mendez, "Integrating Safety, Operations, Security, and Safeguards into the Design of Small Modular Reactors: A Handbook," SAND2013-9429, Sandia National Laboratories, Albuquerque, NM, 2013.

- *Load-Following*: However, thermal stresses on the plant can significantly reduce its lifetime. Power conversion efficiency is also affected when operating at off-nominal power levels. There are methods to address needs for fast response (on the order of seconds) after power conversion has occurred. Slow response can be addressed via the reactor response, thereby alleviating much of the concern related to thermal stresses.

- *Highest Possible Physical Security*: As discussed with operations and safety features, physical security is linked to other considerations. However, methodologies have been specifically developed to optimize security aspects of SMRs within the larger CE process. Utilizing a combination of secure-by-design practices (below-grade siting, redundant safety equipment, and CE, and RIMES[3]) and statistical approaches for evaluating the probability of adversary success, the highest possible physical security can be achieved. The goal of this work is to create a system that is inherently secure enough that all active guard forces can be eliminated, or at the very least minimized. As part of this goal, a measure for assessing the risk to the plant has to be developed to the extent that the regulator will accept the design as being secure enough to reduce/eliminate the guard force currently required. It should also be noted that cyber security should be included in the overall “security” design/assessment.[1,2,4,5]

- *Proliferation Resistant:* Currently, methods are employed to retrofit existing facilities with appropriate tracking and surveillance systems. New systems should incorporate methodologies that concurrently optimize with security, operations, and safety. Risk-informed methodologies must be utilized in all stages of reactor development, beginning with conceptual design and ending with decommissioning. Ideally, this would result in a reactor that never needs to be refueled, and for which decommissioning involves removing a cartridge and shipping it back to the country that developed it (i.e., the USA in this case). Thus, the only tracking required is to ensure that the reactor itself is still located where it is supposed to be. In this way, no fuel can be diverted and tracking is easier for the IAEA.

It should be noted that current views on safety, operations, security, and safeguards suggest that these features must be considered as parts of one large system; they cannot be considered independently if they are to be optimized.

RESPONSE TO RFI QUESTIONS

1. Reactor Context for Enabling Technologies

a. *Reactor design features with best potential for modular nuclear energy systems*
Some aspects of reactor designs that exist and should be incorporated into an optimal design of modular nuclear energy systems include:

[3] Risk Informed Management of Enterprise Systems
[4] Middleton, Bobby D., Marie Y. Arrieta, Robert A. Bari, Lap-Yan Cheng, Meng Yue, “A Method for Applying Markov Techniques to Physical Security Assessment of Advanced Small Modular Reactors,” SAND2013-8497, October, 2013.
[5] Wyss, Gregory D., “Risk-Informed Management of Enterprise Security,” SAND2013-9150P, October, 2013.

Dry Cooling: Some cycles are much better suited to transferring heat to air than others. Traditionally, steam cycles have been used for cooling. However, these cycles transfer heat at constant temperature and therefore are synonymous with low-efficiency power conversion. Some coolants have much more favorable temperature-matching characteristics when combined with air cooling. Supercritical carbon dioxide is one of multiple examples.[6] This leads to more effective heat exchangers and higher-efficiency power conversion. Currently, Sandia is working on some of these technologies. More specificity cannot be included in this RFI response due to Intellectual Property considerations.

Load Following: Load following should be considered, especially for particular markets that have varying energy needs and large renewable integration. For example, certain military bases may have average power demands that are only 25% (or less) of their peak demands. However, those peak demands are critical infrastructure demands and must be met with high reliability. Smart microgrid technologies are available today.[7] There are also techniques to use energy storage as a buffer between the electrical generator and the load, such as parallel power generators on a reactor, where one provides baseload and the second stores energy and responds to transient conditions. These devices can respond to power changes very rapidly (on the order of ½ second), which would allow the reactor to respond much more slowly and still provide a system with fast load following capability.

High Thermal Efficiency: Most power plants today use steam Rankine power conversion cycles. However, the sCO_2 Brayton cycle has much higher power conversion potential, albeit at a higher temperature (45-55% as opposed to ~33% for Rankine). The sCO_2 Brayton cycle allows the much higher efficiency with less complexity than the steam alternative, which is the ultra-supercritical steam Rankine cycle. Significant thermal gains[8] can be based on fractal and swirl geometries for increased radiative and convective heat transfer systems[9,10]. Swirl surfaces can be designed to selectively modify a flow field to produce more desirable heat transfer and fluid dynamics[11,12].

Walkaway-Safe: Plants should be designed to be walkaway safe so that, in the case of an emergency, personnel can leave the plant and the decay heat will be safely transferred to the environment until further action can be taken to address the

[6] Middleton, Bobby D., Salvador Rodriguez, and Matthew Carlson, "Design, Construction, and Operation of a Supercritical Carbon Dioxide (sCO_2) Loop for Investigation of Dry Cooling and Natural Circulation Potential for Use in Advanced Small Modular Reactors Utilizing sCO_2 Power Conversion Cycles," SAND Report, SAND2015-10092, November, 2015.

[7] http://energy.gov/maps/recovery-act-smart-grid-projects

[8] Rodriguez, Salvador, "Enhanced, Passive Cooling for Waterless-Power Production Technologies" Memorandum, June 14, 2016

[9] Dannelley D. and J. Baker, "Natural Convection Fin Performance Using Fractal-Like Geometries", J. of Thermophysics and Heat Transfer, Vol. 26, No. 4, 2012.

[10] Dannelley D. and J. Baker, "Radiant Fin Performance Using Fractal-Like Geometries", J. of Heat Transfer, Vol. 135, 2013.

[11] Rodriguez, S., "Swirling Jets for the Mitigation of Hot Spots and Thermal Stratification in the VHTR Lower Plenum", PhD diss., University of New Mexico, May 2011.

[12] Rodriguez, S. and M. El-Genk, "Recent Advances in Modeling Axisymmetric Swirl and Applications for the Enhancement of Heat Transfer and Flow Mixing", Two Phase Flow, Phase Change and Numerical Modeling, ISBN: 978-953-307-584-6, 2011.

emergency issue. This capability exists, but its efficacy must be demonstrated to the US Nuclear Regulatory Agency (NRC).

Walkaway-Secure: The plant should be designed to be secure to the point that no adversary actions can be taken to place the public at risk during an emergency that requires the plant personnel to evacuate for safety reasons. This requires advanced barriers that are at least equal in security hardness to that of the reactor containment. Examples would include a reactor that is completely enclosed, possibly in a sealed container underground. Such reactor would be inaccessible without especially large equipment that is not available and would be easily detected as it approaches the reactor site.

High Energy Surety: Many potential nuclear customers have a need for highly reliable power supplies to power critical infrastructure systems (e.g., military installations). These sites also need an assured supply of fuel in case of required separation from outside power sources. Sometimes these fuel supplies may be needed for 6 months or more. Meeting these demands with coal or diesel would require enormous on-site storage, which would then make the fuel itself a target. Renewables also present a problem because the energy that they provide is intermittent and therefore do not meet the energy availability requirements. SMRs need to have the following characteristics for energy surety in order to provide these customers with a highly reliable nuclear power source: long refueling cycles, ability to operate independently of external grid, and high energy availability.

Small Emergency Planning Zone: As part of the design process, an emergency planning zone (EPZ) should be as small as possible. Utilizing a dose/distance approach, it may be possible to show that SMRs could have an EPZ that is coincident with the site boundary. This would need to be in accordance with the Environmental Protection Agency's (EPA's) Protective Action Guides (PAGs) and with the NRC's regulations as stated in 10 CFR 52, Chapter 13.3, "Emergency Planning".[13] Utilizing stochastic techniques that are used in other areas, such as fire protection, design of an appropriate EPZ may avoid unnecessary conservatisms that are inherent in the current process, while still meeting all safety requirements.

Low-Uncertainty and Short Manufacturing Lead Times: Many potential customers may be discouraged from ordering an SMR if the time to deliver it is too long or if the delivery time is highly uncertain. Therefore, developing a highly reliable, highly efficient modular manufacturing process is important.

Appropriate Sizing: Many potential customers have a need for a highly reliable energy supply, but do not need the large amounts of power that are produced by today's designs. Identifying the appropriate size for the largest market is crucial. In studies pertaining to military energy needs, the appropriate size seems to range

[13] LaChance, Jeffery, Gregory Baum, Felicia Duran, Kathy Ottinger Farnum, Sabina Jordan, Bobby Middleton, Timothy Wheeler, "Evaluation of the Applicability of Existing Nuclear Power Plant Regulatory Requirements in the U.S. To Advanced Small Modular Reactors," SAND 2013-3683, May, 2013.

from 10 MWe to a maximum of 40 MWe.[14] We also note that electrical utilities are very interested in SMRs, as opposed to conventional light water reactors (LWRs), especially if acquisition cost as a result of appropriate scaling lowers the capital cost and the levelized cost of electricity.

b. Variability of optimum reactor design based on 1 and 300 MW scaling?
The target efficiency should be attainable at a relatively low power (~ 10 MWe) and sustainable through all power levels.

Turbomachinery sizing (mass) should scale as a power law function of reactor power, with the exponent being less than unity. This is presented in equation 1, with ‘S’ representing size of turbomachinery, ‘S_0’ representing the baseline size at a given power level, and ‘a’ representing a number between ½ and ¾.

$$S = S_0 * Power^{a} \tag{1}$$

Natural circulation, dry heat rejection capability, long lifetime, and load following should all be sustainable at powers in the entire range from 1 to 300 MWe.

e. Target power production efficiency and high-performance materials
Commonly available materials can go up to 650° C. Appropriate use of energy conversion systems at that temperature can achieve gross efficiencies higher than 50%.[15] Trade studies are needed to determine the cost-effectiveness of going to higher temperature, where plant cost exceeds the additional revenue generated from increased efficiencies.

2. Materials

a. Materials challenges of vital reactor components
Main material challenges include those related to the qualification of SiC-SiC and C-C core materials, including structural fuel materials. High temperature materials definitely enhance safety margins. They provide valuable heat storage time for passive cooling features to work, and paths for the heat to get out. One particularly useful material that could be qualified for heat exchangers is SiC.

Reactor vessel structural integrity for the life of the plant is crucial, as are fuel integrity and cladding integrity for very long fuel cycles. It should be noted that the NRC will almost certainly require regular testing and inspection of the first few reactors over their lifetime to assure that fuel and other structures are performing as designed.

[14] Middleton, Bobby D., Thomas R. Boland, William E. Schlafli, and Bruce Landrey, “Assessment of Small Modular Reactor Suitability for Use On or Near Air Force Space Command Installations”, SAND Report, SAND2016-2600, March, 2015.
[15] Parma, Edward J., Steven A. Wright, Milton E. Vernon, Darryn D. Fleming, Gary E. Rochau, Ahti J. Suo-Anttila, Ahmad Al Rashdan, and Pavel V. Tsvetkov, “Supercritical CO2 Direct Cycle Gas Fast Reactor (SC-GFR) Concept, SAND Report, SAND2011-2525, May, 2011.

b. Leveraging state of the art computer modeling and simulation codes

From the advanced energy conversion program, both high-temperature and high-pressure environments are required. For the sCO2 Brayton cycle greater than 650°C the economics involved become unfavorable due to the high cost of materials that can handle the pressure and temperature.

Modeling and simulation is essential to the development process. An important foundation for this is good material properties (physical, chemical, and nuclear). Equally important is the use of software structured around state variables in the time domain to more accurately visualize time and amplitude response of the systems. Frequency domain simulations can then be made to better analyze components for fatigue. Recent advances in massively parallel systems, advanced computational methods, and validation and verification should form the cornerstone of computational modeling for innovative, more efficient, secure, environmentally-benign, and reliable energy systems.

Using density functional theory combined with ab initio molecular dynamics simulations, new insight can be gained into the atomistic mechanisms underlying materials degradation. Specifically, defect formation energies, thermo-mechanical stability (phase diagrams), atomic/molecular diffusion rates and activation energies can be predicted with this computational approach for complex structural materials envisioned for use in different modular reactor types. Such models and simulation can help closing the knowledge gaps not investigated experimentally, in order to limit costs, and guide the experimental characterization effort by identifying beforehand possible materials weaknesses under modular reactor operating conditions.

3. Sensors and Controls

a. Technological innovations that could enable substantially autonomous operation

Sandia and the Japan Atomic Energy Agency (JAEA) developed a demonstration for an Advanced Transparency Framework which relies solely in the real-time analysis of intrinsic process data to report changes in diversion risk[16] during facility operations. The application can extract and format system data from an automated physical training model, conduct secure transmissions of the data to a remote location for analysis, integrate and optimize plant design and declared activities into diversion risk calculations, and calculate diversion risk.[17] This type of technology offers great potential for the safe and secure deployment of SMRs that operate automously and monitored remotely. Recognizing the need for sensor data that is intrinsic to the process, these type of systems need to be integrated early in the

[16] Cleary, V., et al, "Incorporation of a Risk Analysis Approach for the Nuclear Fuel Cycle Advanced Transparency Framework", SAND Report, SAND2007-3166, May, 2007.

[17] Cleary, V., et al, "Advanced Transparency Framework Phase II Report: Demonstration and Proof-of-Concept", SAND Report, SAND2008-6023, October, 2008.

design of a modular system in order to avoid costly retrofitting and compatibility issues.

An independent Investment Protection System (IPS) would provide the capability to announce incipient unusual conditions that may require observation, and possibly reduce power or shut down the reactor for unplanned maintenance.

b. Technological innovations that could improve safety and autonomous operations
Overarching an IPS with an independent Nuclear Safety Protection System would provide capabilities to shut down the reactor, start safety related systems, and announce the abnormal condition. When considering international deployment, the ability to remotely monitor and initiate actions should be considered.

c. Data collection and benefits to be obtained from in-core sensors
Robust, in-core sensors would improve the visualization of axial and radial burnup, and with adequate control rod or control drum operation, allow for (a) a better use of the fuel and (b) longer times without refueling. These actions could be automated. There may also be safety benefits since a more homogeneous, axially or radially progressive burnup would reduce risks of potentially troublesome hot spots in the core. Secured data sets in a "cloud" environment would support state of health monitoring by the vendor.

4. Safety and Security: Leveraging Non-Nuclear Experiences

a. Leveraging experience to make transformational improvements
CE practices have been utilized for decades in other industries to reduce risk, improve reliability, and enhance operational aspects of the particular industry utilizing these practices. Sandia has performed preliminary work to develop a means by which CE can be used in the design, construction, and deployment of SMRs.[1, 2, 9, 10] This type of work should be utilized to optimize Safety, Security, Safeguards, and Operability of SMRs.

Control schemes have been proven in coal power generating stations. Digital implementation of these systems is commercially available from Honeywell, Foxboro, and others for oil refinery, petrochemical plants, and coal generating stations. Lockheed Martin is marketing a digital cyber-secure reactor control system.

b. Specific external threats that reactors are exceptionally good or bad at countering
High enrichment reactors are bigger targets to theft and material diversion. Low enriched fuels can be targets to material diversion before they are irradiated. Reactors designed as a cartridge, i.e. reactors delivered to the site with fuel intact so the reactor can be sealed, are not at risk for theft or diversion. Some threats are more easily guarded against than others. However, the defense against each threat may increase the risk related to a different aspect of the system. For example,

locking certain doors may increase security, but decrease the safety of the plant personnel by removing an evacuation route. A better way to approach this issue is to optimize the design of the plant against all threats. This can be achieved through an appropriate use of CE practices that involve assessing all aspects of reactor protections against threats. [9,10,11,12]

5. Marketing Considerations

a. How enabling technologies improve the economics of reactors

Development of a methodology whereby a reactor is designed and built with safety, safeguards, security, operations, and lifetime costs being considered from the very beginning stages of conceptual design would alleviate the need for retrofitting throughout the lifetime of the plant. It would also ensure that the various aspects of the system (safety, security, operability, and safeguards) are globally optimized for maximum benefit to be received from the plant. Since costs are considered from the very beginning of the design, it is assured that any overages are caught before they occur. Currently, throughout the world, many nuclear facilities undergo assessments and retrofitting to ensure that the plant is as secure and proliferation resistant as possible. The United States has spent hundreds of millions of dollars retrofitting facilities throughout the world through programs such as the Global Threat Reduction Initiative and Second Line of Defense, both of which are funded through the National Nuclear Security Administration (NNSA). These programs could be significantly reduced in size if optimal safety, security, and proliferation resistance were to be developed in-design for new nuclear plants.

Fast nuclear spectrum sCO2 technology can be of benefit in that (1) it can temporarily store and deliver significant amounts of heat at high temperatures, which helps efficiency and safety, (2) it shrinks the size of the power conversion systems (turbo-compressors and recuperators), which reduces capital costs, (3) can have higher thermal efficiencies compared with Rankine cycles and, (4) can use the reactor as a breeder/burner reactor to either produce more fuel or to eliminate waste.

b. Markets where economic viability of SMRs is realized in the next 10-20 years

The economic viability of small reactors is likely to be found in niche markets in remote locations where it is very expensive to deliver fuel and yet, need reliable electric power. Many military bases are located in regions where the need for highly reliable electricity is great, but the need for other products such as district heating and liquid fuels is also high. Examples include bases in Alaska and Greenland, where the frigid temperatures would make highly reliable heating capabilities valuable and the need for transportation fuels would make process heat for liquid fuels valuable. Other examples include remote and forward-deployed bases that use liquid fuels; the cost of these fuels can be as high as 50 times the civilian cost due to the risks associated with transporting the fuels to the base.[6]

6. Diagnostic Platform

a. Optimal size, design requirements and features for diagnostic platform
An integrated diagnostic platform would be useful for fuel or component material irradiation and qualification, as well as for fuel irradiation. Certainly, high neutron flux and extreme temperatures would be useful to meet these needs.

b. Diagnostic platform with "common solid core"
A common solid core that is agnostic to nuclear fuels and power conversion may be problematic. It is unclear how time would be allocated to test different concepts or combination of concepts. Funding key technological prototypes, such as Shippingport was to LWRs and Peach Bottom 1 was to gas cooled reactors, might present fewer challenges.

c. Leveraging computer modeling and simulation codes to reduce diagnostic testing
Modeling and simulation is a must-do on every major project. A review of existing codes might be valuable, including the necessary adjustments or rewrites for the fuels and coolants of interest, as well as for safety and scaling, and for the selection and design of innovative energy systems. Modeling and simulation of the technology, economic, security, and diversion risk are essential for R&D prioritization and market considerations.

CONCLUDING REMARKS

Sandia National Laboratories and General Atomics are interested in the development of a relatively small nuclear power plant, on the order of 10 to 40 MWe, for a fast spectrum type that would operate for >10 years without refueling. The reactor core would have a significant negative temperature coefficient of reactivity. No fuel would be stored on site and ultimately, the entire reactor vessel would be returned to a factory in a "reprocessing state"[18]. For better economics and added safety, natural circulation and passive heat transfer systems would be incorporated throughout the system.

We could use UN, UC, and SiC based fuels, as well as SiC-SiC and C-C (ceramic) in core structures, control and shutdown rods, inner reflectors, thermal barriers, insulation cover plates and ducts. This design would have to be qualified to be accepted for the 10-year minimum period.

The reactor core coolant would be supercritical CO_2 (sCO_2), operating in a direct cycle architecture. The energy conversion system would be an sCO_2 Brayton cycle. The Brayton cycle system would operate with a high thermal conversion efficiency above 50%. Heat would be rejected from the system at the sCO_2 critical temperature of 32ºC for dry heat rejection. The dynamics of the configuration would continue down to the reactor decay heat level. These same sCO_2 features would allow for a more reliable and effective

[18] Reprocessing states are approved by IAEA as weapons states and are authorized to reprocess nuclear fuels.

passive cooling as the sCO_2 promotes a strong natural circulation reaching every level of the nuclear vessels.

The small physical size of the system and components would allow for factory production and assembly, and easier transportation and setup in remote locations. The circulating CO_2 needed for the operation of the system could be obtained locally and drawn from the atmosphere.

In the sCO_2 reactor, nuclear power would be monitored outside the reactor by sensing leaking neutrons. Vertically travelling in-core fission chambers for short trips would be used to do flux mapping.

Control systems would be designed for autonomous control utilizing analog electronics and advanced transparency technology to meet cyber-secure state-of-health remote monitoring and possibly include command/disable.

In summary, out of core instrumentation and controls would be used to follow load while in-core instrumentation would be used to periodically monitor power distributions and shape the nuclear flux: load control is fast, and nuclear fuel is burned uniformly. Smart grid technology would be incorporated in a secure configuration to respond to the local grid and protect the reactor.

To reduce risk and cost, we would do detailed modeling and simulation analyses of the entire system from manufacturing to grid-tie. We would then progressively start verification of models at low power in the prototype sCO_2 reactor, followed by a thorough rise to a power program to complete verification and validation.